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Effect of epitaxial layer thickness on the electrical properties of Ti/n-AlGaAs grown by MBE

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ABSTRACT

The effect of epitaxial layer thickness on electrical characteristics of two Ti/n-$Al_{0.33}Ga_{0.67}As$ Schottky barrier diodes was studied in the temperature range of 300–420 K. Comparing the current–voltage (*I–V*) characteristics of two samples with epitaxial layer thicknesses of 2 μm and 1.5 μm discloses that the device with a thinner epitaxial layer has a higher barrier height and hence a lower reverse current. Specifically, we found that increasing the $Al_{0.33}Ga_{0.67}As$ thickness from 1.5 μm to 2 μm would lower the value of the barrier height by ~12% at 300 K. We associated such retrogression of the electrical quality to the presence of deep level traps in the Si:$Al_xGa_{1-x}As$ layer. For both samples we found that the effective barrier height decreases with increasing the annealing temperature. Yet, the sample with a thinner layer showed more stability and less temperature dependence.

Introduction

The conduction mechanism in Schottky barrier diodes (SBDs) made of gallium arsenide (GaAs) [1,2] and its ternary alloys, especially aluminum gallium arsenide ($Al_xGa_{1-x}As$) [3,4], had been studied intensively. In general, the SBD parameters are determined over a wide range of temperatures and doping concentrations in order to understand the nature of the barrier and the conduction mechanism [1]. The Schottky barrier height (SBH) is an important parameter which controls both the width of the depletion region and the carrier current transport through the Metal–Semiconductor interface [5]. It was found that the barrier height of n-$Al_xGa_{1-x}As$ is a function of *x*, and with increasing Al content SBH deviates in a linear way from the value predicted by the "common-anion" rule [6]. In addition to the Al fraction, the interface states play an important role in the determination of SBH and other parameters of Schottky diodes [7]. Henisch [8] stated that the fluctuations in SBHs are unavoidable as they exist even in the most carefully processed devices.

Although AlGaAs Schottky diodes have been investigated for more than four decades, it seems that the only study that explored the influence of epitaxial layer thickness in AlGaAs Schottky diodes was that conveyed by Mari et al. [9] in which they searched for dependence on deep level defects at low temperatures. In this study we report the effect of epitaxial layer thickness on the Schottky barrier height (SBH) and the ideality factor in $Al_{0.33}Ga_{0.67}As$ grown by Molecular Beam Epitaxy (MBE) within the temperature range of 300–420 K.

Experimental details

In this work we used two different n-type Si:$Al_{0.33}Ga_{0.67}As$ Schottky diodes grown by MBE on (100) n^+ GaAs substrate. The epi-structure for both devices, as it is shown in the inset of Fig. 1, consists of 1.02 μm Si-doped GaAs buffer layer followed by n-AlGaAs epitaxial layer with a thickness of 2.0 μm for sample S2, and 1.5 μm for sample S1. Schottky contacts with a diameter of 0.75 μm, for both samples, were processed by evaporating Ti (45 nm)/Au (150 nm) on the top, while ohmic contacts were made by evaporating Ge/Au/Ni/Au on the n^+ GaAs substrate. Both samples S2 and S1 had the same carrier concentration of $2 \times 10^{16}\ cm^{-3}$. *I–V–T* measurements of diodes were performed in the temperature range of 300–420 K by the step of 20 K, and the temperature was controlled by a temperature controller with sensitivity better than ±0.1 K.

Results and discussion

The room temperature *I–V* characteristics for the two examined devices S2 and S1 are shown in Fig. 1. Both Schottky samples exhibited diode like behavior with high asymmetrical

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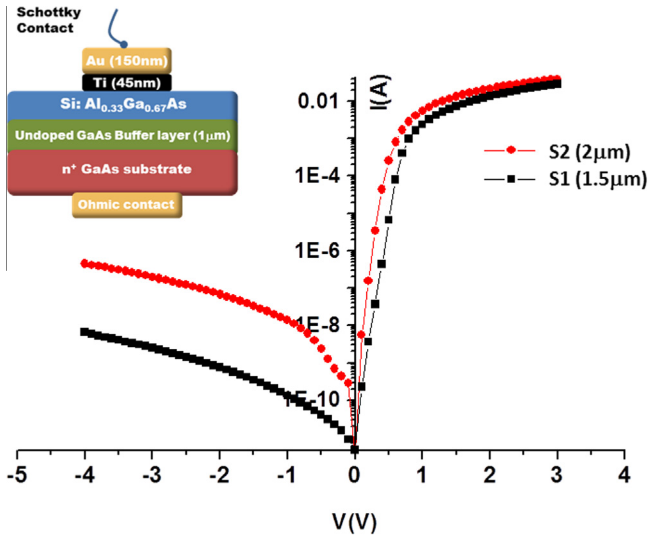

Fig. 1. Room temperature (I–V) characteristics of two Ti-$Al_{0.33}Ga_{0.67}As$ Schottky diodes with epitaxial layer thicknesses of 1.5 μm (S1) and 2 μm (S2). The inset illustrates a schematic structure of samples.

characteristics that indicate the rectification potential of the devices. The asymmetry could be simply defined as the ratio between forward current and reverse currents at specific applied voltage [10]. Based on that definition diodes S1 and S2 have asymmetry values of 10^{-7} and 10^{-5}, respectively, at 1 V. The forward I–V data for both samples is linear on a semi-log scale at lower biases but deviates from linearity at higher biases due to the bulk resistance. Yet, as it is shown in Fig. 1, the reverse current was found to be higher in the sample with a thicker epitaxial layer S2. Using the current–voltage characteristics obtained at room temperature alone could not provide a complete picture about the charge transport process and the quality of the SBDs. Therefore, the temperature dependence of the I–V characteristics are usually employed as it gives detailed information about the conduction mechanism and sheds light on the possible non-ideality effects. For our samples, I–V–T characteristics were performed in the temperature range of 300–420 K. We found that, the forward current (I) and the reverse saturation currents (I_s) for the two devices increased with increasing temperature as illustrated in Fig. 2. This temperature dependence has been noticed before in AlGaAs Schottky diodes [11] and in some other V-III compounds such as AlGaN [12,13].

According to the thermionic emission theory TET, that assumes that the SBH is homogeneous in a SBD, the diode current–voltage relationship can be given by [5]:

$$I = I_s\left[\exp\left(\frac{qV}{nkT}\right) - 1\right] \tag{1}$$

with,

$$I_s = AA^{**}T^2 \exp\left(-\frac{q\Phi_b}{kT}\right) \tag{2}$$

where I_s is the saturation current, q is the electronic charge, V is the applied voltage, k is Boltzmann constant, T is the absolute temperature, A is the contact area, A^{**} is the Richardson constant and Φ_b is the effective barrier height.

From Eq. (2) we can get the Schottky barrier height Φ_b as;

$$\Phi_b = \frac{kT}{q}\ln\left(\frac{AA^{**}T^2}{I_s}\right) \tag{3}$$

The calculated value of the barrier height Φ_b is estimated with Richardson constant A^{**} of 9.48 A cm^{-2} K^{-2} for AlGaAs [14]. The ideality factor n can then be calculated from the following equation [5]

$$n = \frac{q}{kT}\left[\frac{dV}{d\log(I)}\right] \tag{4}$$

The extracted values of the effective barrier height Φ_b and the ideality factor for both devices at different temperatures are listed in Table 1. The values of effective SBH for S1 and S2 varied from 0.851 eV and 0.744 eV at 300 K to 0.786 eV and 0.656 eV at 420 K, respectively. On the other hand, the ideality factor for the thinner layer S1 change from 1.525 at room temperature to 2.211 at 420 K, while the variation was much less on the thicker epitaxial layer. For both samples, we found that the effective barrier height decreases with increasing annealing temperature, whereas the ideality factor was found to increase. Such dependence has been observed before in n-GaAlAs by Wang et al. [14] and Zhang [3] and was attributed by the former to diffusion and subsequent loss of either Ga(A1) or As during annealing. Such diffusion would increase the uncompensated donors at the metal/n-GaAlAs interface resulting in a sufficiently narrow energy barrier that allows carriers to tunnel across it. As a sequence, the reverse current I_s increases with annealing, and hence according to Eq. (3), the effective barrier height should decrease [14]. Their C–V measurements showed that annealing samples at 450 °C for 20 s would increase the interface doping concentration upto 50%. Conversely, Zhang [3] assigned the decrease of effective barrier height with increasing annealing temperature to two possible reasons; the existing defects which may pin the Fermi-level at a higher energy, or the boarding of oxide layer at high annealing temperatures which also plays a major role in decreasing barrier height [3].

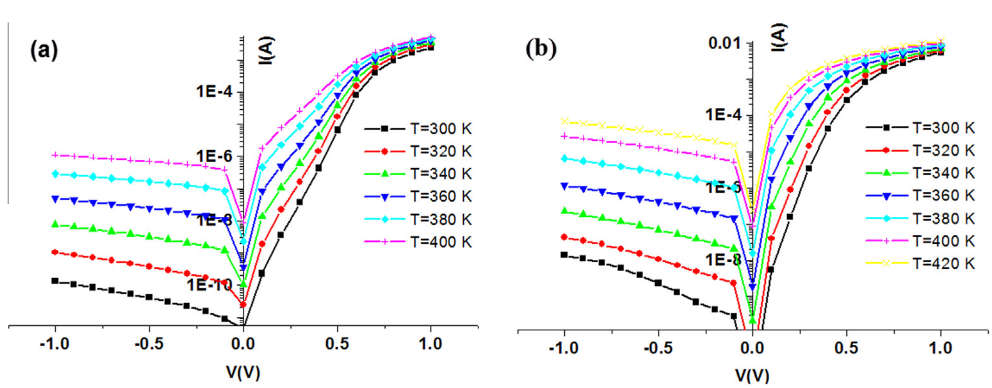

Fig. 2. Semi-log plot of current versus applied voltage at different temperatures for the Ti-AlGaAs Schottky diode with epitaxial layer thickness of (a) 1.5 μm (S1) and (b) 2 μm (S2).

Table 1
The experimental values of SBH and ideality factor for both S1 and S2 devices.

T (K)	Φ_b (eV)		n	
	(S1) 1.5 μm	(S2) 2 μm	(S1) 1.5 μm	(S2) 2 μm
300	0.851	0.744	1.525	1.471
320	0.846	0.733	1.612	1.482
340	0.837	0.711	1.739	1.506
360	0.825	0.692	1.904	1.518
380	0.807	0.667	2.125	1.527
400	0.799	0.653	2.332	1.491
420	0.786	0.656	2.211	1.389

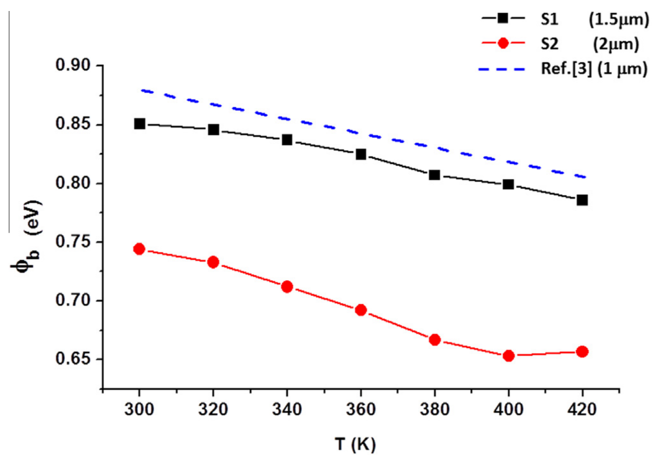

Fig. 3. Effective barrier height Φ_b versus temperature for both diodes S1 and S2. Dashed line represents data obtained from Ref. [3].

Although both samples S1 and S2 showed a similar temperature dependence of barrier height, the values of barrier height Φ_b in the thinner epitaxial layer S1 were higher than those for the thicker one S2. For example, the room temperature values of Φ_b were 0.744 eV and 0.851 eV for the Ti-$Al_{0.33}Ga_{0.67}As$ diodes with epitaxial layer thicknesses of 2 μm (S2) and 1.5 μm (S1), respectively. Since using two specimens could not be sufficient enough to establish a meaningful trend of how such diodes vary with thickness, we adopted the results obtained by Zhang [3] for a similar Ti-$Al_{0.33}Ga_{0.67}As$ diode with epitaxial layer thickness of 1 μm. However, SBH measurements in Zhang's work [3] was only performed at three temperatures; 300 K, 573 K and 673 K, which featured points out of our data range. Thus, we only compared our result to a part of the extracted line between the values measured at 300 K and 573 K. The change of barrier height with temperature for our two samples and the data from Zhang [3] is illustrated in Fig. 3.

It is clear that the device with a thinner epitaxial layer has a higher barrier height, and as the thickness reduces to 1 μm, the value of SBH at room temperature was increased to 0.87 eV. This degradation of the electrical performance of the MBE grown AlGaAs with increasing the layer thickness has been observed before [9] and correlated to creation of deep level defects in GaAs. It is well known that silicon (Si), and other commonly used donors in AlGaAs, give rise to a large concentration of traps in the materials, often referred to as DX centers [15]. Recently, Mari et al. [9] investigated the presence of those centers into the epitaxial Si:$Al_{0.33}Ga_{0.67}As$ layers using two different samples with thicknesses similar to our samples. By executing deep level transient spectroscopy (DLTS) measurements from 10 K to 450 K, they confirmed the existence of a dominant trap in both samples with activation energy of ~0.48 eV which is comparable to the activation energy of the well-known DX center [13]. In addition, they indicated more than one DX-like defect, yet, the number of traps and their concentrations in n-$Al_{0.33}Ga_{0.67}As$ were proportional to the thickness of the epitaxial layer. Their results revealed that a 25% increase in epitaxial layer thickness would increase the DX centers by 6 fold and allow the creation of other types of defects [9]. We believe that the existence of such deep defects is behind the performance degradation of Schottky diode with a thicker epitaxial layer.

Conclusion

In conclusion, the barrier height and ideality factor for two Ti-$Al_{0.33}Ga_{0.67}As$ Schottky diodes had been investigated as a function of their thicknesses in the temperature range of 300 K to 420 K. Both samples showed an ideal thermionic emission behavior as the ideality factors were seen to increase and barrier heights decrease with increasing the temperature. Nevertheless, the effective Schottky barrier for the thinner epitaxial layer was higher within the whole range of temperatures. Such observation maybe ascribed to the presence of more defects such as DX and DX-like centers in the thicker layer that lower the barrier height and degrade the diode performance.

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